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HOW TO BURN ILLINOIS COAL WITHOUT SMOKE

BY

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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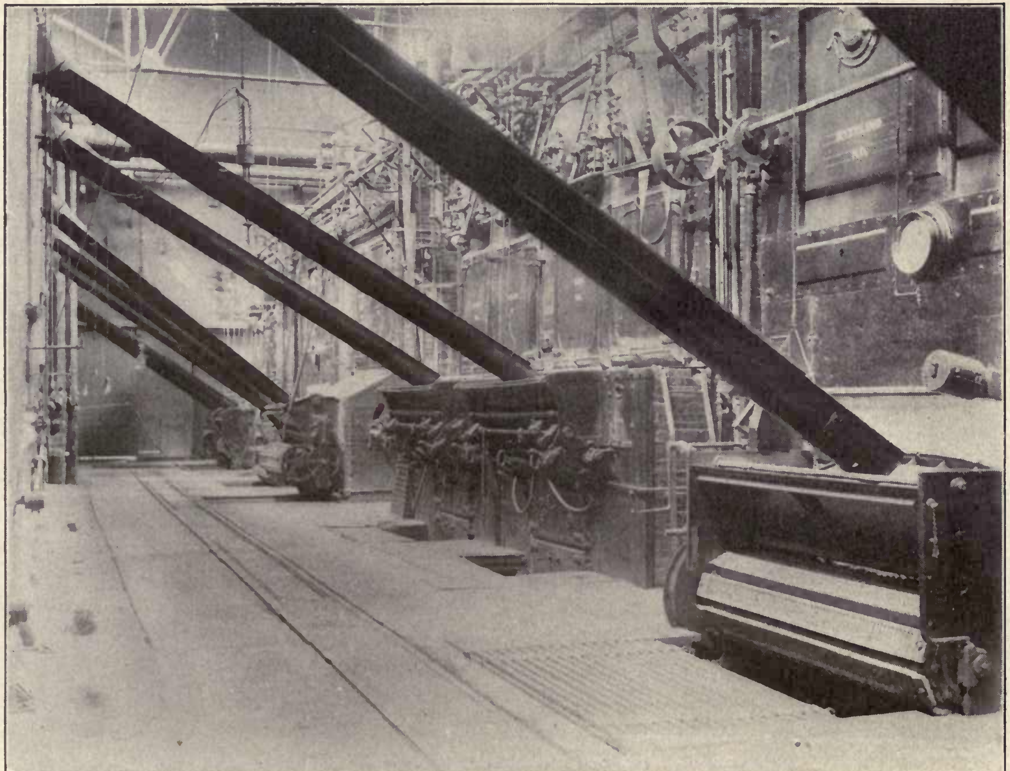

View in Central Heating Station University of Illinois

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN No. 15 AUGUST 1907

HOW TO BURN ILLINOIS COAL WITHOUT SMOKE

BY L. P. BRECKENRIDGE, DIRECTOR OF THE ENGINEERING EXPERIMENT STATION

It is the intention to discuss in this paper the fundamental principles that apply to smokeless furnace construction and operation and to illustrate by means of units in actual operation several ways in which these principles have been satisfactorily applied. With a clear idea of the principles involved, with a knowledge of the character of the coal to be used and the capacity at which it is desired to drive the furnace, there should be little difficulty in designing, constructing and operating stationary boiler furnaces which under ordinary conditions of service will operate with high economy and which will burn Illinois coal without smoke.

The writer does not profess to be acquainted with all the methods that have been found satisfactory for the purpose of smoke prevention, neither does he consider it advisable to describe in detail all the furnaces that are claimed to be capable of burning coal without smoke. All that can be attempted here will be a description of those furnaces with which the writer is personally familiar or which have been examined while in operation and have been found to give satisfactory results.

Perhaps the one thing that has most delayed progress toward success in the smokeless operation of furnaces is the fact that in the past so much in their operation has depended upon the human element. It will doubtless be found that those plants smoke less that are mechanically operated. Such operation is by no means a sure preventive of smoke, as certain constructive features are now well recog-

nized as necessary even with good mechanical stokers if smokeless combustion is to be obtained.

This discussion will be confined to those settings and furnaces that have been found to be most satisfactory in burning Illinois coals without smoke. From a study of the tests of the various coals of the United States, as presented in the reports of the United States Geological Survey fuel testing plant, it seems safe to say that engineers now have sufficient information available to enable them to design boiler furnaces that will burn any coal without smoke. The progress made in this direction during the last five years is surely encouraging and it is confidently believed that the time will soon come when no power plant can offer as an excuse for a smoky chimney the plea that no appliances are available which can be depended upon for smoke prevention. The problem of smoke prevention is the problem of perfect combustion. There is no such thing as smoke consumption and this term should never be used. There is such a thing as perfect combustion and this means smokeless combustion.

The Principles of Smokeless Combustion

The subject of combustion should be familiar to all mechanical engineers. However, as a basis for a thorough understanding of the problems of smoke prevention, a brief review of the principles of combustion may prove acceptable in connection with this subject. In fact, the complete solution of the smoke problem consists in providing furnaces, so constructed and so capable of operation as to make combustion nearly perfect.

Combustion may be defined as a rapid chemical combination, resulting in heat and light. The combining elements are: (a) Oxygen, which is usually derived from atmospheric air; (b) Either carbon or

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This bulletin was prepared at the suggestion of the Conference Committee on Fuel Tests, the members of which are given below. It should be stated, however, that the Committee is in no way responsible for the opinions expressed by the writer.

H. Foster Bain, Director State Geological Survey, Urbana, representing the State Geological Survey; A. Bement, Consulting Engineer, Chicago, the Western Society of Engineers; Edwin H. Cheney, President Fuel Engineering Co., Chicago, the Building Managers' Association of Chicago; F. H. Clark, Supt. Motive Power Burlington Road, C. B. & Q. Ry., Chicago, the Western Railway Club; Adolph Mueller, President H. Mueller Mfg. Co., Decatur, Ill., the Illinois Manufacturers' Association; Carl Scholz, President Coal Valley Mining Co., Chicago, the Illinois Coal Operators' Association; Wm. L. Abbott, Chief Operating Engineer Chicago Edison Co., Chicago, the Board of Trustees, University of Illinois; L. P. Breckenridge, Director Engineering Experiment Station, University of Illinois, Urbana, Ill.

hydrogen, or a compound of the two. Sulphur sometimes appears with carbon and hydrogen, and also combines with oxygen. The substance that is formed by the chemical union is called the product of combustion; and the heat that is produced by the combustion of a unit weight (one pound) of the fuel is called the heat of combustion. This is usually measured in British thermal units (B. t. u.). One B. t. u. is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit. The following table relates to the complete combustion of hydrogen, carbon and sulphur:

COMPLETE COMBUSTION OF THREE ELEMENTS

		PRODUCT OF COMBUSTION		
Element	Chemical Symbol	Name	Chemical Symbol	Heat of Comb'st'n B. t. u. per lb.
Hydrogen	H	Water	H_2O	62000
Carbon	C	Carbon Dioxide	CO_2	14500
Carbon	C	Carbon Monoxide	CO	4400
Sulphur	S	Sulphur Dioxide	SO_2	4000

In the complete combustion of carbon, the product of combustion, it will be observed, is carbon dioxide (CO_2). Each atom of carbon combines with two atoms of oxygen. If sufficient oxygen is not provided, it may happen that each carbon atom will combine with but one oxygen atom, thus forming carbon monoxide (CO). As a result of this incomplete combustion, the heat developed is only 4400 B. t. u. The carbon monoxide may itself combine with oxygen, according to the formula

$$CO + O = CO_2$$

and the heat developed will be the difference, 14 500 — 4400 = 10 100 B. t. u. per pound of carbon in the carbon monoxide.

A knowledge of the relative weights of these elementary atoms gives a direct means of computing the amount of oxygen required for combustion. The weights are as follows:

H..........1	O..........16
C..........12	S..........32

In the burning of hydrogen to H_2O, two atoms of hydrogen, each of weight 1 combine with one atom of oxygen, weight 16; hence the ratio of oxygen to hydrogen is 16 : 2 = 8 : 1, i.e., 8 lb. of oxygen are required for the combustion of 1 lb. of hydrogen, and

there results 8 + 1 = 9 lb. of water. This combination with others may conveniently be presented in a tabular form as follows:

THE COMBUSTION OF IMPORTANT ELEMENTS WITH OXYGEN

Elements	Chemical Equation	Relative Weights	Weights pounds
Hydrogen to H_2O	$2H + O = H_2O$	$(2 \times 1) + 16 = 18$	$1 + 8 = 9$
Carbon to CO_2	$C + 2O = CO_2$	$12 + (2 \times 16) = 44$	$1 + 2\ 2/3 = 3\ 2/3$
Carbon to CO	$C + O = CO$	$12 + 16 = 28$	$1 + 1\ 1/3 = 2\ 1/3$
Sulphur to SO_2	$S + 2O = SO_2$	$32 + (2 \times 16) = 64$	$1 + 1 = 2$
Methane or Marsh Gas	$(CH_4) + 4O = CO_2 + 2H_2O$	$(12 + 4) + (4 \times 16) = 12 + (2 \times 16) + 2(2 + 16)$	$1 + 4 = 2.75 + 2.25$

When the oxygen needed for combustion is taken from the atmosphere, the nitrogen always present must be taken into consideration. Nitrogen takes no part in the combustion but mingles with the products of combustion, absorbs heat from them and passes away with them. Approximately, it takes 4.25 lb. of air to furnish 1 lb. of oxygen; the remaining 3.25 lb. are nitrogen. When the combustion of the different elements takes place in air the resulting relative weights are modified on account of the presence of the nitrogen. This is exhibited below.

THE COMBUSTION OF IMPORTANT ELEMENTS IN AIR

Elements	Chemical Equation	Relative Weights	Weights pounds
Carbon in Air	$C + Air = CO_2 + 7.43N$*	$12 + (2 \times 4.25 \times 16) = 44 + 104$	$1 + 11.33 = 3.67 + 8.66$
Marsh Gas in Air	$CH_4 + Air = CO_2 + 2H_2O + 14.86N$	$(12 + 4) + (4 \times 4.25 \times 16) = 44 + (2 \times 18) + 208$	$1 + 17 = 2.75 + 2.25 + 13$

* The atomic weight of nitrogen is 14.

It will be seen from the above table that to burn 1 lb. of carbon 11.33 lb. of air must be supplied. The 8.66 lb. of nitrogen contained in the weight of air pass away with the 3.67 lb. of carbon dioxide (CO_2) formed by the combustion. For the complete combustion of 1 lb. of marsh gas, 17 lb. of air are required. Chemical combinations of carbon and hydrogen, the so-called hydrocarbons, play an important part in the burning of coal, particularly in those coals of large volatile content. The most important of these are the following:

Hydrocarbon Element	Chemical Symbol	Heat of Combustion
Methane or Marsh Gas	CH_4	24020 B. t. u.
Ethylene or Olefiant Gas	C_2H_4	21930 B. t. u.
Acetylene	C_2H_2	21850 B. t. u.

At the ordinary temperature and atmospheric pressure, a pound of air has a volume of about 13.1 cu. ft. Using this value, the following (round numbers) are obtained for the theoretical amount of air required for the complete combustion of various fuels:

AMOUNT OF AIR REQUIRED TO BURN ONE POUND OF VARIOUS FUELS

Kind of Fuel	Carbon	Hydrogen	Sulphur	Methane
Weight of Air (lb.)	11.33	34	4.25	17
Volume of Air (cu. ft.)	150	445	55	220

The heat developed by the combustion is absorbed by the products of combustion, and as a result, the temperature of these gases rises in a marked degree. Thus when carbon is burned in air, the 14 500 B. t. u. developed should heat the 3⅔ lb. of CO_2 and 8⅔ lb. of nitrogen from an initial temperature of perhaps 60° to a calculated final temperature of about 4500°. The actual final temperature, for reasons to be explained presently, is considerably lower. The products of combustion act as a vehicle, carrying the heat developed by combustion to its final destination.

It may perhaps be profitable to picture an ideal perfect combustion, and then inquire in what ways actual combustion falls short of the ideal. The given fuel, composed of carbon, various volatile hydrocarbon gases, and perhaps sulphur, is to be burned in air. Theoretically, each atom of the fuel finds and seizes upon the number of oxygen atoms with which it will combine. Each atom will meet with two oxygen atoms at a temperature sufficiently high for ignition. They will combine, and the resulting CO_2 will pass out of the furnace, carrying with it the heat arising from the combustion; likewise with the hydrogen and sulphur atoms. No more air will be delivered than is just sufficient to furnish the exact number of oxygen atoms, and no carbon or hydrogen atoms will pass out of the furnace without finding oxygen atoms with which they can combine.

Actual combustion deviates from ideal conditions in many respects. If only the theoretical amount of air is supplied, on account of the difficulty of properly mingling the fuel and air, some of the fuel atoms will not find oxygen atoms, and will escape uncombined. Or some of the carbon may burn to carbon monoxide instead of to carbon dioxide, and the CO will escape without further combustion. It is found in practice that to insure complete combustion, an excess of air must be furnished. This excess is usually 50 per cent, and may reach 100 per cent; i.e., while only 11.3 lb. of air are required for the com-

plete combustion of 1 lb. of carbon, it is usually necessary to furnish 18 to 24 lb. Since the heat of combustion is distributed throughout the excess of air introduced into the furnace as well as the products of combustion, the furnace temperature is lowered by the presence of the extra air.

In another important particular, the actual state of affairs is likely to be quite different from the ideal combustion outlined above. Carbon and oxygen atoms will not unite unless a certain temperature, the ignition temperature, is reached. In parts of the furnace, the temperature may fall below the ignition point because of the inrush of an excess of air, or because of cold bounding surfaces. As a result, carbon particles, even in the presence of plenty of oxygen, will refuse to burn. Let us further illustrate these principles by the use of some familiar examples.

If the reader understands why a torch smokes, why a flat wick is used in a lamp, why a circular burner is provided for the Argand or student lamp, why a chimney is provided for oil lamps, why a fish tail flame was used in early gas lighting, or why a vacuum bulb is provided for the incandescent lamp; if he understands these things, and most of us do, he will, it is believed, be able easily to see what conditions are necessary for perfect combustion in boiler furnaces.

If any fuel is to be burned without smoke it must be supplied with the correct amount of air. The torch smokes because the large round wick brings up oil, especially in the center, to which air cannot be supplied. If the air supply through the center tube of our student lamp is shut off a smoking flame results. The candle with the small wick is an advance over the candle supplied with the large wick. The flame from the flat wick has an extended surface for air supply, while the circular burner not only has maximum surface for air supply, but the air coming up through the center of the tube is heated, making it still better suited to aid combustion and burn a large amount of oil. Thus it is that we have successfully solved the problem of burning a large oil supply without smoke. If we try to increase the oil consumption and turn up our lamps too high, they smoke, and because they are in the room with us we immediately turn them down. Furnaces burning coal sometimes smoke just because they are forced too hard, and because the top of the chimney is not in our room, but in the public's pure air we do not turn them down, but let them smoke.

Air correct in amount is a necessity for complete combustion and the simple experiments which we have all been making with our oil and gas flames should be sufficient evidence to us that only when we are able to supply our furnaces with the correct amount of air shall we be able to control the smoke which it is so easy to make. How much easier our problem would be if, as in the lamp, we could see all that was taking place and could regulate all by a simple knurled brass handle.

Smoke Production

Having briefly outlined the essential features of perfect combustion let us turn our attention to the conditions present when the combustion is imperfect, usually resulting in smoke. The products of combustion, carbon dioxide, steam and sulphur dioxide are colorless gases. If nothing except these gases escaped from a chimney, there would be no smoke problem. Visible smoke is due to the volatile hydrocarbons which all bituminous coal contains to a greater or less extent, and which are driven off when the coal is heated. The percentage of volatile matter in coal varies widely; thus in the eastern anthracites, it may be as low as 3 per cent, while in the western lignites, it may rise as high as 50 per cent. The larger the percentage of volatile matter, the more liable is the coal to produce smoke, and the more difficult is smoke prevention.

When coal is heated in the furnace, the volatile content, consisting largely of methane and ethylene, is driven off. If the volatile gases should not enter any region of high temperature, they would simply pass out of the chimney with the products of combustion. But, as a rule, the gases are ignited, and burn, much as ordinary illuminating gas burns. The phenomena connected with the combustion of volatile gases are, however, not simple. There are grounds for supposing that a hydrocarbon, at a sufficiently high temperature, is decomposed into its elements. If oxygen is present, the hydrogen at once combines with it. The carbon particles will not combine with oxygen except under favorable conditions; if there is not a sufficient supply of air, or if it is not at a sufficiently high temperature, the carbon particles refuse to combine and are carried along with the products of combustion to be afterwards deposited as soot, or appear at the top of the chimney as smoke. This may be shown by an equation as follows:

$$C_2H_4 + 2\,O = 2H_2O + 2\,C$$

Ethylene and oxygen form water vapor and soot.

The mere explanation of the formation of black smoke suggests immediately the means that should be employed to prevent such formation. Evidently sufficient air must be furnished to burn the carbon particles liberated from the hydrocarbon gases; this air must be at a high temperature. If too great a volume of cold air is admitted to the furnace, and if at the same time the bounding surfaces of the combustion space are boiler plates or tubes of relatively low temperature, the result will be a low temperature in the space above the fuel, and it will be impossible to burn the carbon content of the volatile matter. To insure proper combustion, after the gases are driven from the coal, they should intimately mingle with sufficient air in a chamber, in which high temperature can be maintained. The heating surface of the boiler should not be permitted to come in contact with these gases until combustion has been completed.

Losses Due to Smoking Chimneys

The destruction of property or the effect upon the health of the community due to the smoke nuisance are matters upon which there is not an opportunity to dwell in this article. Both of these subjects are now matters of common every-day knowledge to the residents of our American cities. Something should be said, however, about the fuel losses due to smoking chimneys. The absence of smoke by no means indicates perfect combustion. It may simply mean excessive air dilution and this means uneconomical operation. Statements are frequently seen in the daily press to the effect that one-quarter or one-third of the fuel burned goes off in the black smoke issuing from the chimney. Such statements are very far from the truth. It is doubtful if the black carbon particles which issue from chimneys and which we call soot ever amount to one per cent of the fuel burned in any furnace. It takes but a small amount of soot to give a dense black color to smoke. If it were to save only these soot particles we could not afford expensive stoker and furnace settings. The appearance of black smoke is fortunately the signal of incomplete combustion and the losses due to this cause are many times the losses due to the carrying away of the small soot particles. This matter is well stated by that practical and clear writer, Wm. H. Booth, as follows:

"It is customary to speak of smoke and the smoke nuisance as though black smoke were the only feature of imperfect combustion

that demanded a remedy. But it cannot be too strongly emphasized that the visible impurities of the waste gases from factory chimneys are the least harmful part of their constituents; and that the invisible gases, which too often escape as the result of imperfect combustion, are far more detrimental in their effects upon vegetation and upon the health of the community. These invisible gases consist of unaltered hydrocarbons and of carbon monoxide; their presence is due either to deficiency of air, or to the lack of the requisite temperature in the combustion area. Smoke is the visible sign of the presence of these deleterious gases. It is, therefore, a useful signal of something wrong in the combustion process. Smoke ought to be attacked, not only because it brings dirt and depression in its train, but because its emission is accompanied by that of gases which are directly detrimental to the health of all living things, and at the same time carry away much heat from the plant of the fuel user. Both on humanitarian and economic grounds its suppression is called for*."

If there is a deficient air supply part of the carbon atoms will not find enough oxygen atoms with which to combine and there will be a considerable part of the escaping gases leaving the chimney as carbon monoxide (CO) instead of being burned to carbon dioxide (CO_2). For each pound of carbon burned only to carbon monoxide (CO) there will be a loss of approximately 10 000 heat units and this constitutes the great source of loss so frequently referred to as the loss due to incomplete combustion. This loss may readily amount to 5 per cent of the total heat in the coal. The density of the accompanying smoke may or may not be an indication of the proportion, though the loss due to carbon monoxide in perfectly smokeless chimney gases in practice will usually not exceed 0.05 of one per cent. Smokelessness is a relatively safe indication that the total heat has been liberated. Unfortunately it gives no indication of the degree of efficiency with which the heat is being utilized. The problem from the standpoint of the operator demands smokelessness with a minimum air supply. Losses due to sensible heat in the stack gases while seldom rising higher than 32 per cent of the total heat may be as low as 10 to 12 per cent without smoke or incomplete combustion. These figures are found in the fuel test reports of the United States Geological Survey under Illinois coals. The following tabulation will serve to indicate

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SMOKE PREVENTION AND FUEL ECONOMY, Booth and Kershaw—Archibald, Constable & Co., London, 1904.

how the heat generated in a boiler furnace may be distributed when operating under poor, average and best conditions.

AN APPROXIMATE HEAT DISTRIBUTION FROM ILLINOIS COAL

	Percentage of Heat		
	1 Poor Condition	2 Average Condition	3 Best Condition
1. Absorbed by the boiler	50.0	65.0	75.0
2. Carried away in dry chimney gases	24.0	16.0	10.0
3. Radiation and unaccounted for osses	15.0	12.0	10.0
4. Moisture formed by burning of hydrogen	4.0	3.5	3.0
5. Evaporating moisture in coal	2.0	2.0	1.5
6. Incomplete combustion of carbon	5.0	1.5	0.5
Total heat	100.0	100.0	100.0

The per cents given in the last column of this tabulation are seldom attained in present practice, but they are by no means impossible. They represent conditions for which we should continually strive. Losses of 20 to 25 per cent are not unusual, both with and without smoke. Too little air is wrong. Too much air is wrong. Absolutely complete combustion can be obtained using Illinois coal burned on an automatic stoker with as low as 30 per cent excess of air. The question is one of proper furnace construction to meet the requirements of the fuel coupled with a good fireman and an intelligent use of instruments which will tell him at all times the conditions of the combustion and draft.

It has been stated elsewhere, what relation should exist between the weight of coal burned and the weight and volume of air required for perfect combustion. It is sometimes more striking, however, to bring out this point, by using a larger unit than the single pound. Take for instance, a 1000 horse-power boiler plant. Many such plants would burn 5000 lb. of coal an hour; the air supplied would weigh 100 000 lb. and the volume of this air at a chimney temperature of 500 degrees Fahr. would be about 2 400 000 cu. feet. The chimney for this plant must therefore discharge nearly 105 000 lb. (52.2 tons) of gases into the atmosphere each hour; that is, for each ton of coal burned the chimney will discharge from 18 to 22 tons of gases. To keep these gases of the right color and composition for 90 per cent of the time is the problem to be solved. Chimneys will still be needed when the so-called smoke problem is solved. The popular solution consists

in changing the color of the gases flowing from the chimney from black to a light gray, that is from No. 5 to No. 1 on the Ringelmann chart. At least this is all that the public and the smoke inspector will demand. But even when this problem is well solved our chimneys must continue to discharge immense volumes of heated gases, and these gases will often carry with them fine particles of ash which cannot be burned; all of which may produce something of that disagreeable haze which floats over manufacturing cities. The dense black smoke from chimneys is certainly a nuisance. It can be stopped for about 90 per cent of the time, and if this is accomplished a most wonderful improvement will be observed in the atmosphere of our cities. If smoke is not largely prevented in large cities it will be because of laxity in carrying out the provisions of the law, combined with the indifference of power plant owners, rather than because of a lack of furnaces and boiler settings which are available for successfully burning bituminous coal without smoke.

The Observation of Smoke

From the point of view of the general public there are but two kinds of chimneys, those that smoke and those that do not smoke. The emission of black smoke for a short period say of three minutes of an hour is sometimes enough to leave the impression on the casual observer that the chimney smokes all the time. It is therefore important that there should be some way devised for estimating the relative blackness of smoke and some plan adopted for recording the length of time during which smoke of varying degrees of blackness is emitted from chimneys. Numerous schemes have been proposed to accomplish this purpose. One of the most scientific of these plans is that invented by Professor Ringelmann of Paris.*

"In making observations of the smoke proceeding from a chimney, four cards ruled like those in the cut, (See Fig. 1), together with a card printed in solid black and another left entirely white, are placed in a horizontal row and hung at a point about 50 feet from the observer and as nearly as convenient in line with the chimney. At this distance the lines become invisible, and the cards appear to be of different shades of gray, ranging from very light gray to almost black. The observer glances from the smoke coming from the chimney to the cards, which are numbered from 0 to 5, determines which card most nearly

* Trans. A. S. M. E., Vol. XXI, Dec., 1899.

corresponds with the color of the smoke, and makes a record accordingly, noting the time. Observations should be made continuously during say one minute, and the estimated average density during that minute recorded, and so on, records being made once every minute. The average of all the records made during a boiler test is taken as the average figure for the smoke density during the test, and the whole of the record is plotted on cross section paper, (See Fig. 2), in order to show how the smoke varied in density from time to time. A rule by which the cards may be reproduced is given by Professor Ringelmann as follows:

Card 0. All white.

Card 1. Black lines 1 mm. thick, 10 mm. apart, leaving spaces 9 mm. square.

Card 2. Lines 2.3 mm. thick, spaces 7.7 mm. square.

Card 3. Lines 3.7 mm. thick, spaces 6.3 mm. square.

Card 4. Lines 5.5 mm. thick, spaces 4.5 mm. square.

Card 5. All black.

The cards as printed on page 13 are much smaller than those used by Professor Ringlemann. The thickness and spacing of the lines are in the same proportion, but reduced to one-half size."

The smoke observations reported in the government fuel tests made by the Technologic Branch of the U. S. G. S. are all based on the Ringelmann chart. This chart has, therefore, been adopted in the reports of fuel tests made by the Engineering Experiment Station and the numbers used in its bulletins refer to this scale.

An observer soon becomes skilled in taking smoke records and when several observers have been trained to the system their records are very nearly alike. In fact one soon becomes so familiar with the scale of densities that he no longer needs the actual charts for comparison, but may be trusted to take the record without the aid of the chart. An attempt has been made to illustrate smoke densities in the plate shown in Fig. 2. Many difficulties surrounded the preparation and printing of such a plate and it is inserted with some misgivings. It is believed, however, that if it should prove successful it will give some reader a better idea of the value of the scale numbers 1 to 5, used to denote smoke densities than will the pictures of the Ringelmann charts.

When a record of a smoking chimney is desired numerous ways are adopted for showing its behavior. For many records a column of the scale density numbers is sufficient, set of course opposite the inter-

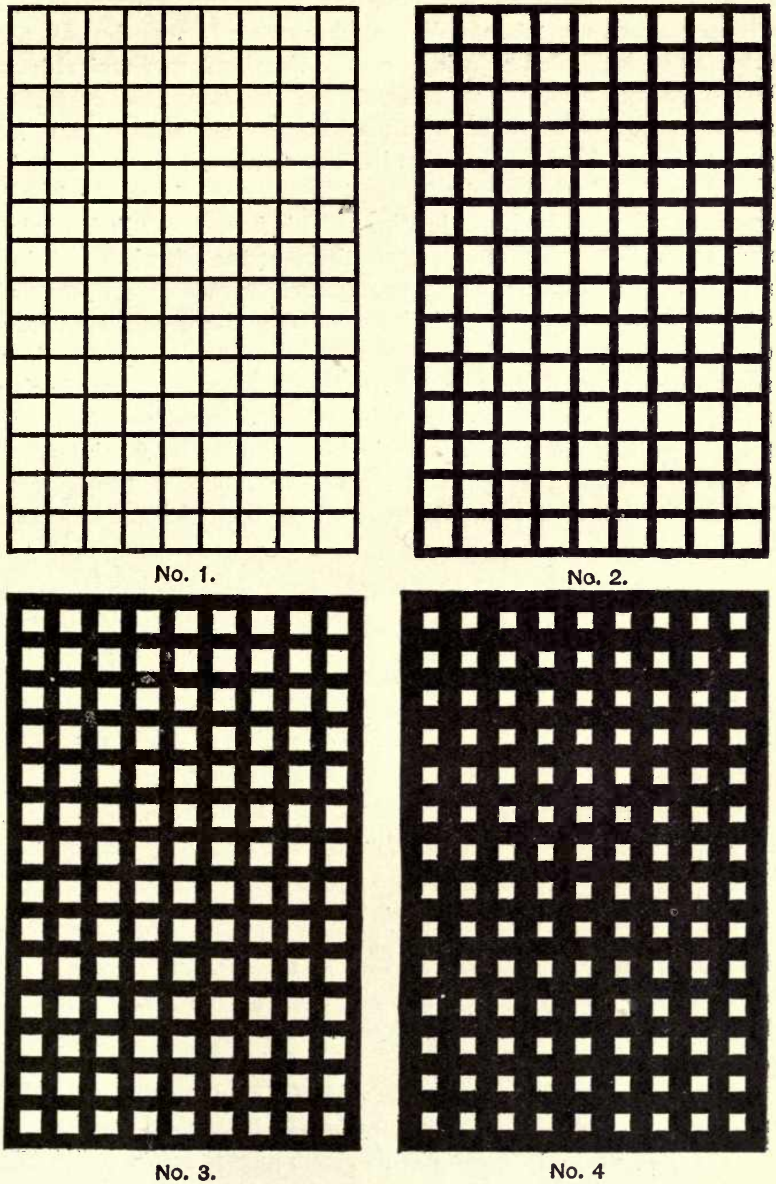

FIG. 1 THE RINGELMANN SCALE FOR GRADING THE DENSITY OF SMOKE

vals of time which are deemed short enough for the purpose for which the observations are taken. Where many records must be taken the work may be facilitated by using some of the simple mechanical devices which have been perfected for this purpose. These usually consist of a drum rotated by clockwork, and a marking pen movable by hand leaving a record on suitable paper that has been wrapped on the drum. The form of smoke chart record adopted in the work of the Engineering Experiment Station is shown in Fig. 3. This form needs little explanation. The scale density numbers are those at the left of the sectioned plates and these densities are approximately shown at the top under their respective numbers. It is intended that the time scale shall be chosen and placed along the zero horizontal lines. This time scale will vary according to the character of the tests being made. Graphic charts are for many purposes much preferable to any other scheme for exhibiting the continuous operation of chimneys supposed or claimed to be smokeless, and they are particularly useful when comparing several stacks for the same interval of time, or when changes made in a setting are being studied.

Furnaces and Boiler Settings Suitable for Burning Illinois Coal Without Smoke

General Principles of Construction.—Various writers on boilers and furnaces have enunciated the principles of smoke prevention in different ways. In "Steam Boiler Economy," Wm. Kent says:

"Coal can be burned without smoke provided:

(a) The gases are distilled from the coal slowly.

(b) That the gases when distilled are brought into intimate contact with very hot air.

(c) That they are burned in a hot fire-brick chamber.

(d) That while burning they are not allowed to come in contact with comparatively cool surfaces, such as the shell or tubes of a steam boiler; this means that the gases shall have sufficient space and time in which to burn before they are allowed to come in contact with the boiler surfaces."

Mr. A. Bement, who has made a careful study of the smoke problem, suggests* some slight modifications of the Kent form of statement. He says: "Professor Kent's requirements may be modified as to two features as follows:

*The Suppression of Industrial Smoke with Particular Reference to Steam Boilers.—Journal Western Society of Engineers. Dec., 1906.

(a) That the evolution of gas from the coal shall proceed uniformly.

(b) That the gases which are distilled uniformly from the coal shall enter a fire-brick chamber of either sufficient length to allow the flames to become entirely consumed naturally or that the chamber be provided with such auxiliary mixing and baffling devices as will cause the gases to be artificially mixed together before the exit of the chamber is reached."

Further discussing the subject, Mr. Bement presents clearly the importance of uniformity of the evolution of the volatile gases and points out that the lack of uniformity of the evolution of the gases when coal is hand-fired must be supplemented by efficient mixing devices such as fire brick piers or special baffling. The matter presented in this bulletin only corroborates the testimony presented in Mr. Bement's article, and except for the fact that possibly this publication may reach a larger number of manufacturers throughout the state than will Mr. Bement's paper, it need hardly have been presented.

Any fuel may be burned economically and without smoke if it is mixed with the proper amount of air at a proper temperature.

This is the statement of the smoke problem that the writer has sometimes presented. We have then three forms of presentation of the problem. To the fuel expert any one of these forms is sufficiently clear. It does, however, require some familiarity with the problem to understand just what these statements mean. To the owner who is trying to make his plant stop smoking or who must decide between several types of furnaces or boilers that he wishes to install, all these carefully stated formulas are often meaningless and provoking. What the owner wishes to know is what furnaces and boilers are in the market that are really suitable for burning Illinois coals without smoke. It is in many ways unfortunate that there are so many independent manufacturers of furnaces and boilers. Both furnace and boiler should preferably be sold and installed by the same company. It may not be long before this will be so. At least, the boiler companies should furnish complete plans with their boilers including the furnace. Possibly

The Peabody Atlas—Shipping Mines and Coal Railroads in the Central Commercial District of the United States, with Chemical, Geological and Engineering Data. A. Bement, 1906. 16¾×18 in. 149 pp. An extensive and valuable work relating to the central coal fields of the United States, published by the Peabody Coal Co., Chicago. The section devoted to smokeless furnaces and smoke suppression contains many excellent illustrations which should be of great help to engineers who wish to be fully informed on this subject.

this matter might be left to the consulting engineers, but many firms buy their boilers directly from the boiler companies and follow the same setting plans that have been developed and found efficient with anthracite or other eastern coals, and often these are entirely unsuited for Illinois coals having such a high volatile content.

Much confusion has doubtless arisen and many disappointments have followed because of the fact that furnaces found entirely suitable for eastern coals have been tried further west without modification and have proved themselves failures. Some of the furnaces described in this paper would not be suitable for use with eastern coals. The use of the Dutch oven furnace, which was common before the chain grate stoker, doubtless paved the way for the various forms of automatic stokers which made use of the good points recognized in the old forms of the Dutch oven furnaces.

The history of the growth and development of the smokeless furnace could well form the subject for an engineering article. It is hoped that some one may soon make the steps in such a development a matter of record. The writer certainly makes no claims for discovery of invention in this connection. He has, however, experimented with many methods of firing, many devices for smoke prevention and many variations in furnace construction, not only in Illinois, but also in Pennsylvania and in New England.

The boiler plant at the University of Illinois at Urbana, Illinois, consists of 2000 horse-power in nine units. During the last two years this plant has been operated practically without objectionable smoke fully 90 per cent of the time. Over 200 separate boiler tests have been made in this plant to determine the economy of operation and for a study of furnace conditions. Many changes have been made in the constructive features of the furnaces and boiler baffling with the view of studying the smoke problem. Many varieties of coals have been tested for smokelessness. The character of the installation is indicated below.

Boiler No. 1. Babcock & Wilcox (Special high-pressure boiler 275 lb.), equipped with B. & W. chain grate stoker, usual vertical baffling, capacity 150 H. P. This unit can be run without smoke at capacities from 50 to 120 per cent.

Boiler No. 2. Babcock & Wilcox standard boiler (150 lb.) equipped with B. & W. chain grate stoker, usual vertical baffling, capacity 150 H. P. This unit can be run without smoke at capacities from 50 to 120 per cent.

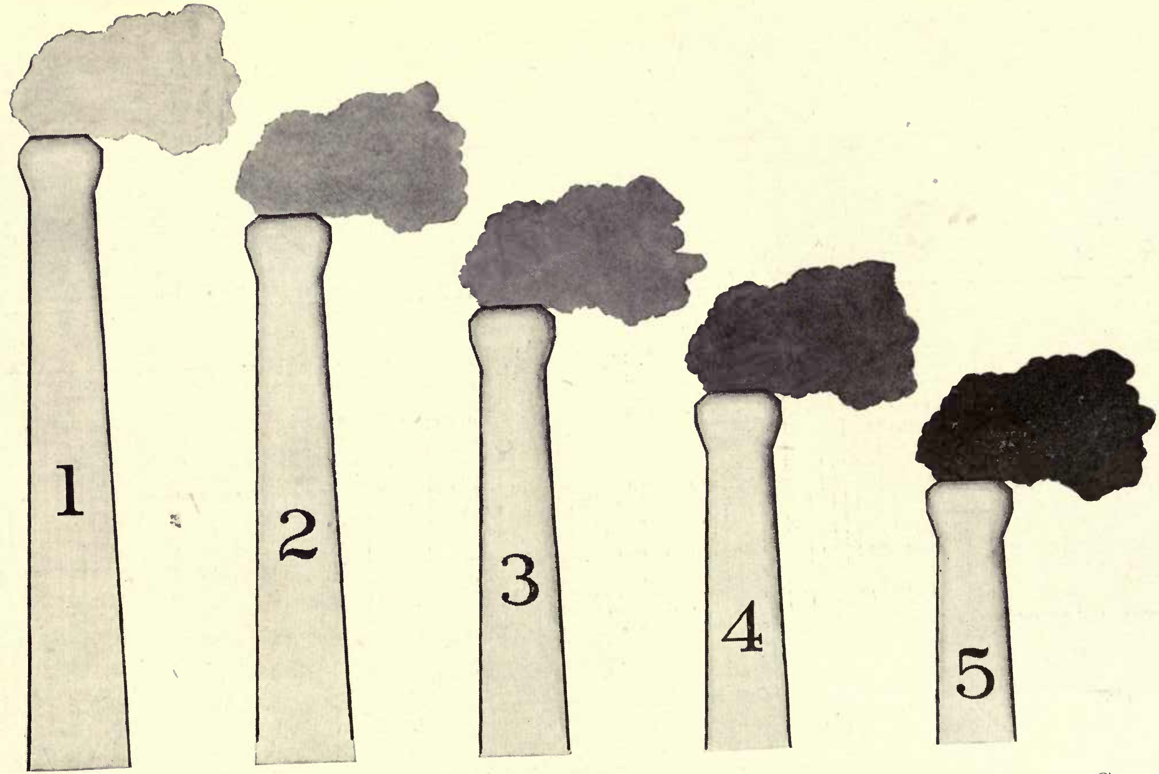

Fig. 2 Chimneys Illustrating Smoke Densities Approximating the Ringelmann Smoke Charts

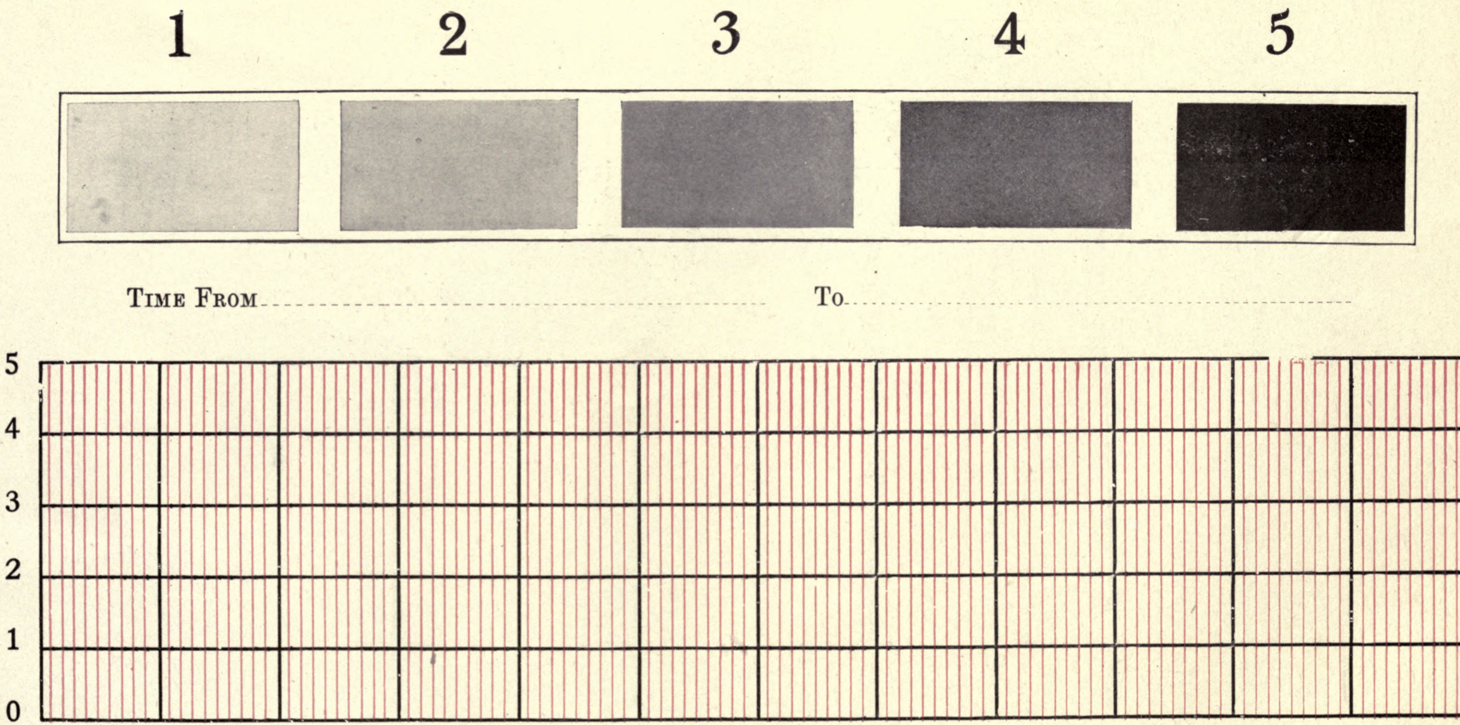

FIG. 3. SECTION OF SMOKE CHART RECORD

Boiler No. 3. Stirling standard boiler (150 lb.) equipped with Green chain grate stoker, usual baffling and combustion arches, capacity 260 H. P. Setting shown in Fig. 4. This unit can be run without smoke at capacities from 50 to 140 per cent.

Boiler No. 4. National water tube boiler (150 lb.), formerly equipped with Murphy furnace but now equipped with Green chain grate stoker: usual vertical baffling, capacity 250 H. P. This unit can be run without smoke at capacities from 50 to 120 per cent. When equipped with Murphy furnace, this unit was smokeless except when cleaning fires.

Boiler No. 5. Babcock & Wilcox standard boiler (150 lb.), equipped with Roney stokers, usual vertical baffling, capacity 220 H. P. Setting shown in Fig. 5. This unit when handled carefully can be run up to capacity without smoke above No. 2 on the smoke chart. It requires careful attention and at capacities above 100 per cent cannot be run without objectionable smoke. This boiler is an exact duplicate of unit No. 6.

Boiler No. 6. Babcock & Wilcox standard boiler (150 lb.), equipped with Roney stokers, special baffling making tile roof furnace. Boiler and stoker duplicate of unit No. 5. Capacity 220 H. P. Setting shown in Fig. 6. This unit can be run without smoke at capacities from 50 to 100 per cent.

Boiler No. 7. Stirling standard boiler (150 lb.) equipped with Stirling bar grate stoker, usual baffling and combustion arches, same as Boiler No. 3, capacity 260 H. P. This unit can be run without smoke at capacities from 50 to 140 per cent.

Boiler No. 8. Stirling standard boiler (150 lb.). Exact duplicate of boiler No. 7, capacity 260 H. P.

Boiler No. 9. (Engineering Experiment Station special test boiler), Heine standard boiler (150 lb.) equipped with Green chain grate, usual combustion arch, tile roof furnace, adjustable water back at bridge wall, capacity 210 H. P. Setting shown in Fig 7. This unit can be run without smoke at capacities from 50 to 140 per cent.

A study of the various units mentioned above reveals the fact that any one of the four well known types of boilers may be set over at least three well known types of automatic stokers and be operated

without objectionable smoke. The opinion of the writer, doubtless held by most engineers, is that the boiler has very little to do with the smoke problem, except perhaps that some types of boilers lend themselves more easily to the necessary furnace construction, which is of the utmost importance when perfect combustion is desired.

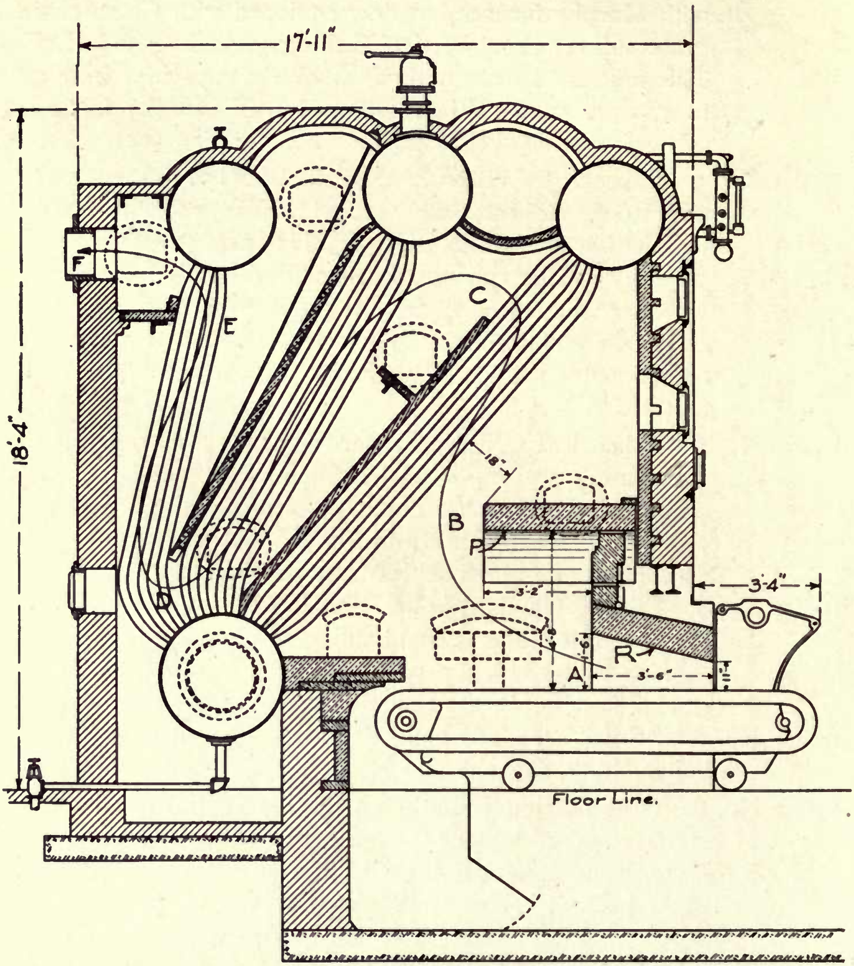

Fig. 4 Stirling Standard 260 H. P. Boiler Equipped with Chain Grates

(Operates easily without smoke at capacities from 50 to 140 per cent).

Description of the Settings Shown by the Figures

In the figures which accompany this article there are shown several types of boilers and furnaces that have been found suitable for burning Illinois coals without smoke. These settings have been operated under the immediate observation of the writer. Each figure is supplied with a title which is at the same time a description of the setting and an indication of the possibility of its smokeless operation under varying conditions of service. The drawings themselves are sufficient to illustrate the conditions that must be fulfilled to secure smokelessness when using boilers of these types under usual service capacities. The stack draft available for boilers No. 1 to 8 is 0.75 in. to 1.0 in. supplied by a brick chimney 150 feet high with an inside diameter of 6 feet. Boiler No. 9 is supplied with an economizer and

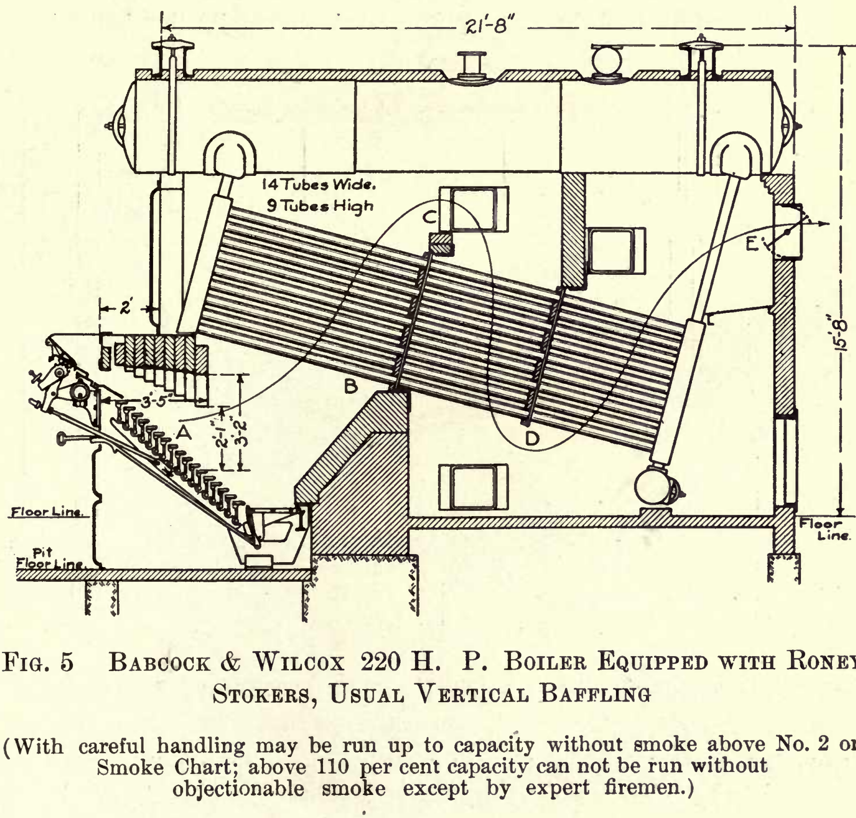

Fig. 5 Babcock & Wilcox 220 H. P. Boiler Equipped with Roney Stokers, Usual Vertical Baffling

(With careful handling may be run up to capacity without smoke above No. 2 on Smoke Chart; above 110 per cent capacity can not be run without objectionable smoke except by expert firemen.)

an induced draft fan permitting higher rates of combustion than are possible in the other settings.

In all of these settings it has been found necessary to pay particular attention to the coking arch under which the fresh charge of coal is being delivered. It seems to be true that over chain grates this arch should be inclined upwards more for a light than for a heavy draft. It is also believed that the arch of the Roney stoker should be kept well down toward the grates. The dimensions given in Fig 5 have given good results in these settings.

When Illinois coal is being burned in any furnace it is essential that the volatile products of combustion should be uniformly distilled from the coal and mixed with sufficient air at a high temperature. To accomplish this, particularly to maintain a high temperature, the mingling air and products of combustion must be kept away from the tubes or plates of the boiler which are comparatively cool, and which would therefore cool the gases before complete combustion had taken

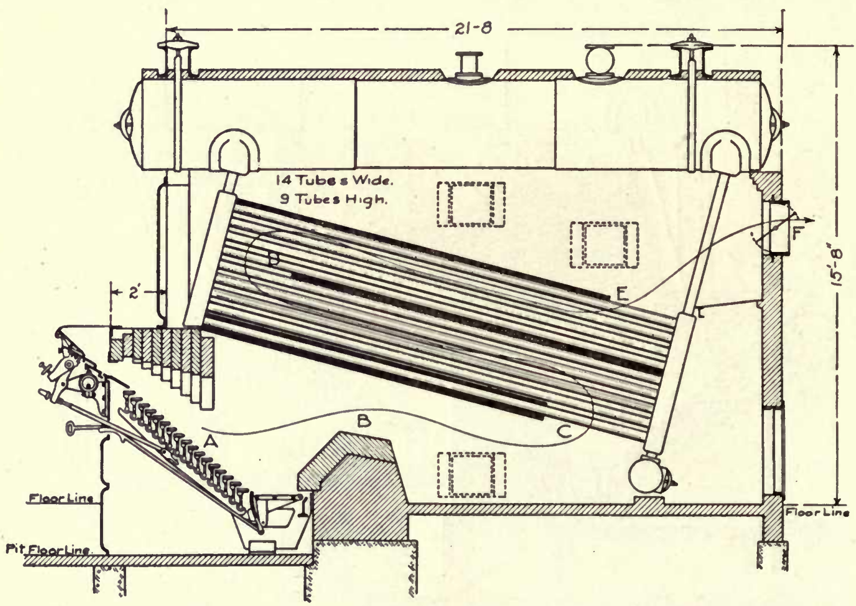

FIG. 6 BABCOCK & WILCOX 220 H. P. BOILER EQUIPPED WITH RONEY STOKER

(Setting as in Fig. 2, but arranged with different baffling, forming a tile roof furnace. This unit can be run at capacities from 50 to 100 per cent without smoke.)

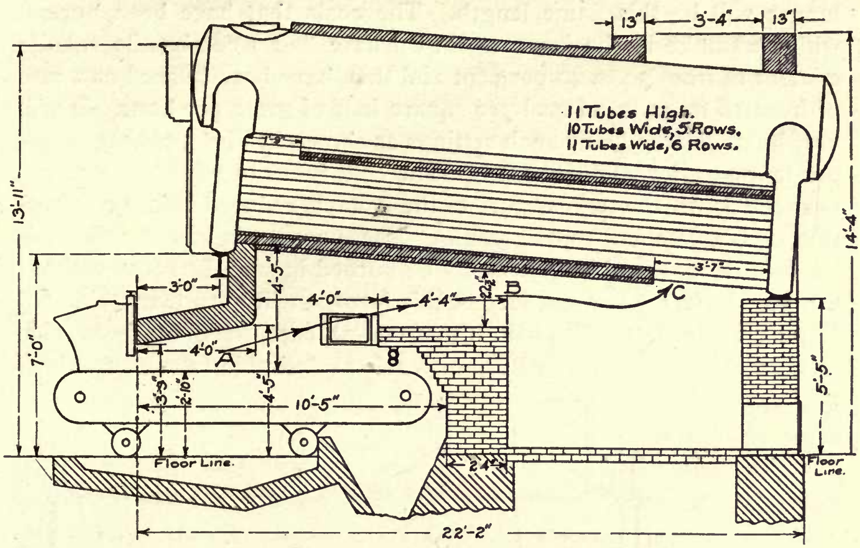

FIG. 7 HEINE STANDARD 210 H. P. BOILER EQUIPPED WITH GREEN CHAIN GRATE, COMBUSTION ARCH, TILE ROOF FURNACE, ADJUSTABLE WATER-BACK AT BRIDGE WALL

(This is the Engineering Experiment Station Boiler furnished with induced draft. It can be run easily without smoke at capacities from 50 to 140 per cent; almost impossible to make smoke with this setting under any condition of operation.)

place. It is for the reason just mentioned that such forms of furnaces as shown in Fig. 6, 7, and 8 are planned. Special forms of fire clay tile are designed to be hung on the water tubes of boilers that are directly over the fire. The tiles form the roof of the furnace and prevent the hot gases, which are still not properly mixed, from coming in contact with the cooler tubes which are surrounded by the tiles. These tiles are made in various forms, three types being shown in Fig. 9. The kind shown at C makes a smooth flat roof for the furnace and has been found very satisfactory.

The length of a tile roof furnace or the distance of flame traveled before reaching the cool tube surface must evidently depend upon the total volume of volatile products distilled from the coal on the grate in a given time, which must be mixed with the air supply before the cooling tubes are reached. The higher the coal is in volatile content or the higher the rate of combustion per square foot of grate area, the

longer will be this flame length. The coals that have been burned without smoke in the furnaces shown have had a combustile volatile content of from 30 to 40 per cent and they have been burned at a rate of from 16 to 40 lb. of coal per square foot of grate per hour. It will now be understood why such settings as shown in Fig. 5 cannot be depended upon for smokelessness. The cold tubes of the boiler are too near the flame, the temperature of the flame is reduced before combustion is complete and smoke results. There are coals low in combustible volatile matter that may easily be burned in such furnaces without smoke. In fact, when not forced, this furnace will burn many kinds of Illinois coals, but only with the greatest care have we been able to burn the usual grades of Illinois coals at desirable rates of combus-

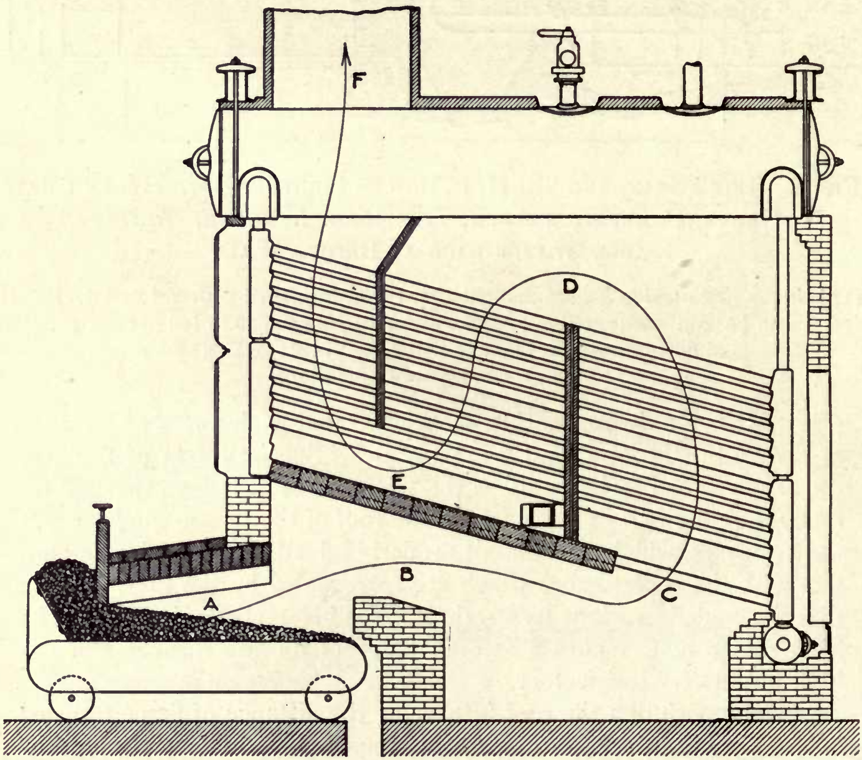

FIG. 8 SMOKE-PROOF STEAM GENERATOR DESCRIBED BY A. BEMENT, W. S. E. PAPER, OCTOBER, 1906.

(A satisfactory plan when proper attention is given to the draft available and to the areas of the gas passages.)

tion (24 to 30 lb.) without objectionable smoke, (No. 2 to 3½ on the smoke chart).

When the baffling shown in Fig. 6 was installed a series of smoke trials was arranged with this setting and the setting shown in Fig. 5. The results shown by these trials were disappointing and unsatisfactory. Lack of sufficient draft made it impossible to run setting Fig. 6 above its rated capacity. Under this condition there was little difference in the smoke from the two furnaces. This result suggests that changes in baffling of existing plants must be made with careful consideration of draft areas available or capacities may be cut down to an undesirable extent. The capacity possible with the setting shown in Fig. 6 proved to be about 90 per cent to 98 per cent while the capacity of the settings shown in Fig. 5 with the same coal was from 100 per cent to 120 per cent. The setting of Fig. 6 should prove satisfactory with higher draft pressures or by increased areas possible with a larger number of tubes in the vertical rows. From what has already been said about cool tubes, an inspection of the settings in Fig. 4, of a Stirling boiler over a chain grate stoker, might convey the impression that such a setting would produce smoke because of the absence of tile on the tubes below the path of the flame A B C. This setting has, however, proved to be a satisfactory and smokeless one. Looking at the progress of combustion through the side openings provided in the three settings of this character in the University plant, it is seen that the flame rolls along over the edges of the two arches shown and is by these arches completely mixed. No part of the tubes below the flame path A B C is enveloped by the flames; therefore the tubes have little cooling effect. It is also very evident that the lower ends of the tubes next the furnace fulfill their duty as heat transmitters by taking care of a very considerable part of the radiant heat which is available in large quantities at that point. Boilers of this type are now being manufactured at almost any desired height, the necessary capacity being furnished by increased width. They have proved very satisfactory, smokeless furnaces being easily arranged under them.

The Heine boiler set over a Green chain grate shown in Fig. 7 is the boiler installed by the Engineering Experiment Station for fuel tests with Illinois coals. This boiler is exactly like the Heine boiler used in the government fuel tests at St. Louis.* In this setting, how-

*The characteristic feature of these two settings is a tile roof furnace, originating in 1901 with W. L. Abbott, at the Harrison St. station of the Commonwealth Edison Co., Chicago.

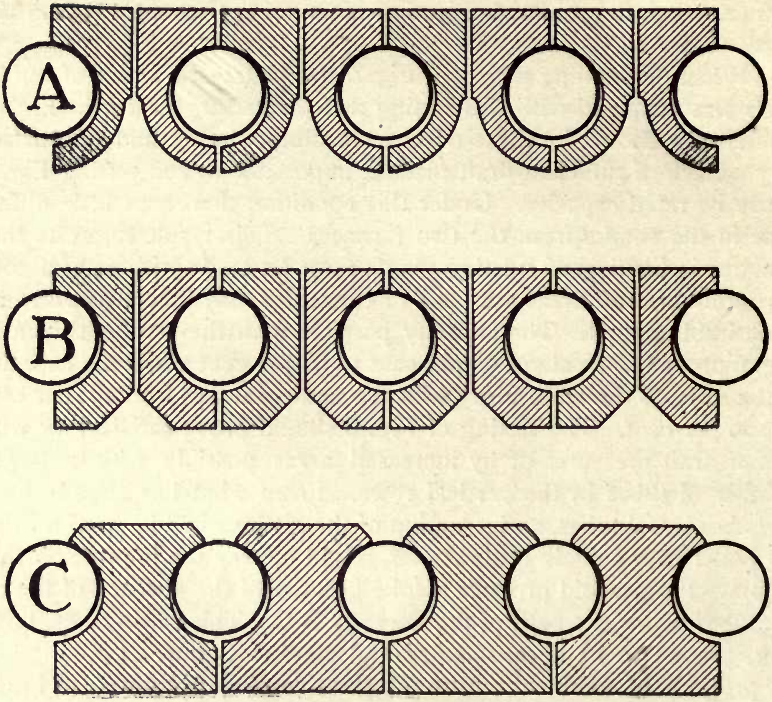

FIG. 9 THREE TYPES OF TILE ROOFS FOR BOILER FURNACES

ever, we have a stoker furnace while the government boilers were set with hand-fired furnaces, evidently necessary where coals from many sections of the country were to be tested. The setting shown in Fig. 7 is provided with an economizer and a large induced draft fan making high rates of combustion possible. This setting is smokeless under the many and varied conditions of operation which have thus far been applied to it. Over 100 trials of about 10 hours' duration of various kinds of Illinois coal have been made in this setting. In all of these trials the smoke record has been "No smoke all day." This is the setting to which the writer has referred in several recent talks by saying that in this setting it has been impossible to make smoke. In order to justify any such statement, attention is called to the results of a series of tests made with this setting for the express purpose of smoke production if such was possible under apparently adverse conditions.

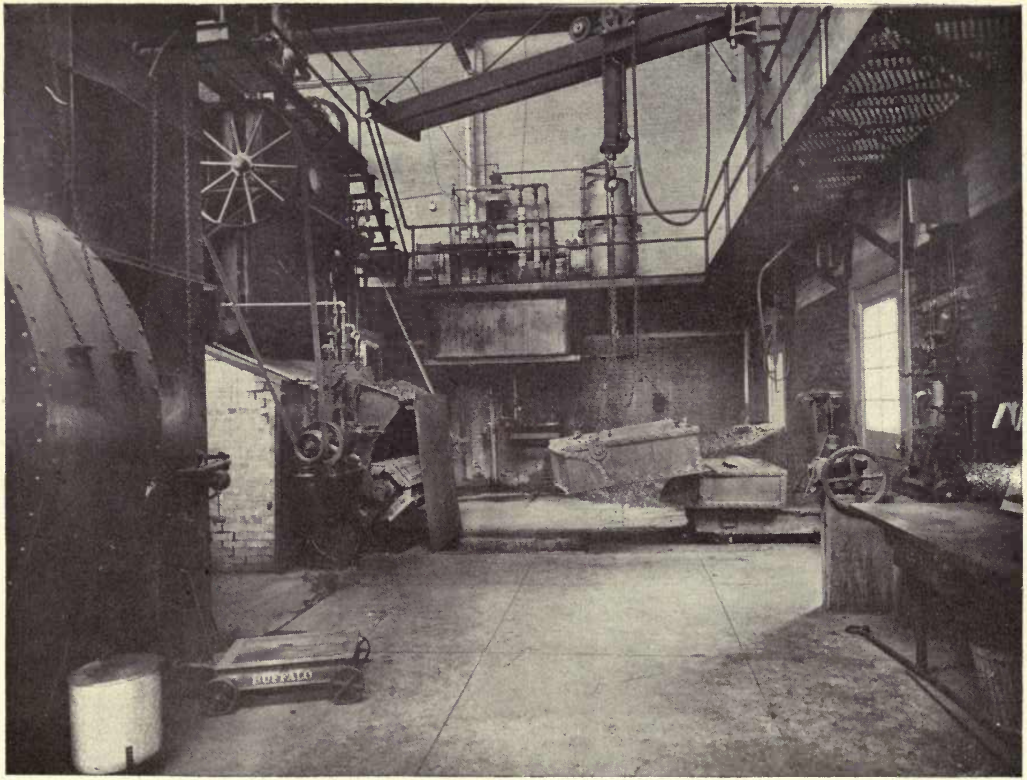

Fig. 10 General View of Engineering Experiment Station Fuel Testing Plant 210 H. P. Heine Boiler, Weighing Tanks, Ash Car and Hoist, Induced Draft

Those who desire to grasp the simple yet fundamental principles of smokeless combustion for Illinois coals should thoughtfully consider just how this furnace fulfills the conditions of perfect combustion, as stated on page 15 in the words of Kent, Bement and the writer. A detailed account of the process in this furnace may well bear repetition here.

The fresh coal, fairly uniform in size, advances slowly from the hopper along on the grate toward the furnace where the temperature is very high. The combustible volatile matter is continually being distilled from the coal, more and more rapidly, but with much uniformity, while it is passing under the combustion arch. Some of the necessary air flows in through the coal in the hopper, more through the grate under the arch, but by far the most flows through the redhot coals on that part of the grate beyond the arch. This air is thus heated and made ready for combining with the volatile products flowing from beneath the arch, and all together mix and roll along on the bottom of the tiles forming the roof of the furnace.

The bottom row of boiler tubes is covered with suitably formed tiles, which prevent the still actively mingling gases from being cooled by coming in contact with the tubes, and so the combustion processes go on until completed before reaching C, a point before the gases pass in among the cooling tubes. The tiles in the adjoining rows touch each other so that no gases pass between them. In such a furnace as this the smoke problem is settled somewhere between B and C. When the total volume of combustible material distilled from the coal is quite large in a given interval of time, the flame length may reach to C, while for smaller volumes the flame may end at B. Thus it is that the flame length indicates the end of the combustion processes and gives us valuable information concerning the proportions of smokeless furnaces.

It is important in the operation of this or any form of mechanical stoker that abundant opportunity be afforded for inspecting the condition of the fires and the progress of combustion. Appliances for continually indicating the composition of the escaping gases should be considered a necessity in all large and well managed plants.

The character of the draft apparatus available with this setting made it possible to make sudden changes in the rate of combustion. The rate of travel of the chain grate was easily adjusted by a throttle governor on the independent steam engine in driving the grate. The rate of combustion could be calculated very closely from the thickness

of the fuel bed and the rate of grate feed, by reference to the large number of tests already made with this unit. These special smoke tests were run on four different days, and on each day eight changes in condition of operation were made. The thicknesses of fire used were four, five, six and seven inches. The capacities varied from 60 to 150 per cent of the rated capacity (210 H. P.) of the boiler. The character and the size of the coal used are indicated in the tables. The results of these tests amply justify the conclusion that this type of furnace may be depended upon to operate even under adverse conditions without objectionable smoke, for out of a total of 32 tests in only six cases could any smoke be seen coming from the stack, and in three of these six smoke did not exceed No. 1 on the smoke chart. Where the most smoke was made, it was only No. 1½ and 2½, and here it will be observed that the draft had been suddenly reduced in the breeching, amounting to the condition of closing the damper with a brisk fire.

TABLE 1

SPECIAL SMOKE TESTS OF ILLINOIS COAL WITH A CHAIN GRATE STOKER, TILE ROOF FURNACE AND HEINE WATER TUBE BOILER, WITH VARYING RATES OF COMBUSTION. February 5, 1907. Coal--Washed, Size No. 4[a].

ITEM / Test No.	1	2	3	4	5	6	7	8
Time, Start	8:10	9:00	9:30	9:56	1:00	1:30	2:00	2:35
Time, Stop	9:00	9:30	9:56	1:00	1:30	2:00	2:35	2:47
Thickness of Fuel Bed	4	4	4	4	4	4	4	4
Draft Pressure in Furnace	.092	.110	.180	.095	.098	.057	.050	.080
Draft Pressure in Breeching	.430	.600	1.260	.580	.500	.250	.090	.240
Lbs. Coal Burned per sq. ft. of Grate Surface as Fired	31.4	39.3	45.5	——	35.8	28.3	23.4	——
Do. Dry Coal	27.8	34.8	40.4	——	31.7	25.5	20.7	——
Mean per cent of Rated Capacity Developed	112	126	155	——	135	109	91	——
Flue Gas Temperature, °F	629	671	762	661	659	600	521	560
Temperature over grate	2500	2550	2620	——	2530	2390	2310	——
Temperature back of Bridge Wall	2470	2550	2710	——	2490	2390	2310	——
Per cent CO_2	12.0	12.8	12.2	——	12.8	12.8	14.4	——
Smoke	0	½	1	0[b]	0	1½	2½	0

(*a*) Moisture in coal as fired, 11.3 per cent; ash, 7.5 per cent.
(*b*) Grate stopped for repairs.

TABLE 2

SPECIAL SMOKE TESTS OF ILLINOIS COAL WITH A CHAIN GRATE STOKER, TILE ROOF FURNACE AND HEINE WATER TUBE BOILER, WITH VARYING RATES OF COMBUSTION. February 9, 1907.—Washed, Size No. 2[a].

ITEM	Test No.	1	2	3	4	5	6	7	8
Time, Start		8:03	9:00	10:00	11:00	12:00	1:00	2:00	3:00
Time, Stop		9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00
Thickness of Fuel Bed		6	6	6	6	6	6	6	6
Draft Pressure in Furnace		.126	.154	.178	.122	.12	.088	.060	.120
Draft Pressure in Breeching		.56	.73	.96	.56	.50	.23	.11	.35
Lbs. Coal Burned per sq. ft. of Grate Surface as Fired		27.5	28.2	34.9	28.5	23.7	21.5	21.0	31.3
Do. Dry Coal		24.5	25.5	31.3	25.4	21.5	19.3	18.7	27.7
Mean per cent of Rated Capacity Developed		92	109	119	112	111	89	67	99
Flue Gas Temperature, °F		671	679	707	663	642	574	516	562
Temperature over Grate		2375	2485	2420	2340		2280	2235	2465
Temperature back of Bridge Wall		2305	2385	2340	2360		2210	2090	2475
Per cent CO_2		10.1	10.1	9.1	10.0	9.8	11.6	11.4	11.8
Smoke		0	0	0	0	0	$\frac{1}{8}$	0	$1\frac{1}{2}$[b]

(*a*) Moisture in coal as fired, 11 per cent; ash, 7.97 per cent.
(*b*) Much unconsumed coke forced over back end, thus increasing the ratio of volatile carbon in the fuel actually consumed.

The results of these experiments are given in Tables 1, 2, 3 and 4, and they certainly demonstrate the possibilities of smokeless combustion of some typical Illinois coals.

It is not within the scope of this bulletin to enter into any lengthy discussion of the results as shown by these tables. It should, however, be stated that this setting has been operated not only without smoke, but also with economy, as may be seen by inspection of Table 5. The complete record of the results of the economy tests made under this boiler will form the subject of a separate bulletin soon to be published.

RELATION BETWEEN CAPACITY AT WHICH BOILERS ARE DRIVEN AND THE TENDENCY OF THEIR FURNACES TO SMOKE

There is a rate of driving a boiler furnace which, if exceeded, will result in producing smoke. This rate varies for different types of

furnaces and for the various methods of baffling or kinds of mixing piers used. It also varies for different kinds of coals. A strong draft will make a large air supply possible, and allow thicker fires or finer coal to be used. The possibility of sufficient air makes a furnace smokeless when an insufficient supply caused by a weak draft might cause the production of smoke. There is an always increasing tendency to drive boilers and furnaces a little harder. Boilers that were purchased for 1000 H. P. a few years ago are now being forced to 1400 and 1600 H. P. This means of course larger grate areas and a much higher rate of combustion per unit of grate area. As far as the boilers are concerned, they seem to be ready and willing to transmit about the same proportion of the heat available to the boiler as ever. It is doubtful if constructive furnace details have kept pace with the demands for the higher rates of combustion and at the same time have

TABLE 3

SPECIAL SMOKE TESTS OF ILLINOIS COAL WITH A CHAIN GRATE STOKER, TILE ROOF FURNACE AND HEINE WATER TUBE BOILER, WITH VARYING RATES OF COMBUSTION. February 11, 1907. Coal—1½-inch Screenings. Ordinary Grade for Tests, 1, 2, 3, 4, 5[a]. Poor Grade for Tests, 6, 7, 8.

ITEM	Test No.	1	2	3	4	5	6	7	8
Time, Start		8:05	9:00	10:00	11:00	12:00	1:00	2:00	3:00
Time, Stop		9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00
Thickness of Fuel Bed		5	5	5	5	5	7	7	7
Draft Pressure in Furnace		.202	.252	.40	.23	.108	.302	.355	.58
Draft Pressure in Breeching		1.21	1.30	——	1.12	.23	1.48	1.21	——
Lbs. Coal Burned per sq. ft. of Grate Surface as Fired		32.7	35.4	39.3	30.2	12.4	46.5	26.8	26.2
Do. Dry Coal		27.4	30.0	33.2	25.5	10.5	——	——	——
Mean per cent of Rated Capacity Developed		87	103	106	84	56	106	75	68
Flue Gas Temperature, °F		674	704	718	650	542	674	646	625
Temperature over Grate		2360	2400	2615	2489	2180	2530	2425	2485
Temperature Back of Bridge Wall		——	——	——	——	——	——	——	——
Per cent CO_2		6.8	7.6	6.6	7.2	6.2	7.0	4.7	4.3
Smoke		0	0	0	0	0	0	0	0

(*a*) Moisture in coal as fired, 14.23 per cent; ash, 15.4 per cent.

TABLE 4

SPECIAL SMOKE TESTS OF ILLINOIS COAL WITH A CHAIN GRATE STOKER, TILE ROOF FURNACE AND HEINE WATER TUBE BOILER, WITH VARYING RATES OF COMBUSTION. February 12, 1907. Coal—1½-inch Screenings, selected [a].

ITEM	Test No.	1	2	3	4	5	6	7	8
Time, Start		8:00	9:00	10:00	11:00	12:00	1:00	2:00	3:00
Time, Stop		9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00
Thickness of Fuel Bed		6	6	6	6	6	5	5	5
Draft Pressure in Furnace		.18	.25	.20	.10	.06	.195	.10	.05
Draft Pressure in Breeching		1.00+	1.5+	.93	.36	.21	1.20	.57	.15
Lbs. Coal Burned per sq. ft. of Grate Surface as Fired		28.3	32	28.3	23.9	16.8	31.0	26.5	22.6
Do. Dry Coal		24.2	27.3	24.2	20.4	14.3	26.5	22.6	19.3
Mean per cent of Rated Capacity Developed		89.8	85	91	85	74	100	92	80
Flue Gas Temperature °F		649	662	639	588	544	676	624	540
Temperature over Grate		2450	2525	2450	2435	2525	2305	2470	2490
Temperature Back of Bridge Wall									
Per cent CO_2		7	5.9	7	9.9	9.7	7.3	8.7	11.8
Smoke		0	0	0	0	0	0	0	0

(*a*) Moisture in coal as fired, 14.6 per cent; ash, 9.48 per cent.

provided efficient smoke preventing plans. In other words when boilers are forced much over 30 per cent of their rated capacity the probability of smoke from their furnaces rapidly increases. Nothing inherent in the boiler itself is at all responsible for smoking furnaces, for as elsewhere pointed out it is the total amount of volatile combustible evolved in the furnace per unit of time that imposes duties upon those constructive features of the furnace and combustion chamber which are designed to furnish the proper amount of suitably warmed air to the furnace and to provide for its effective mingling before the products of combustion reach the cooling surfaces of the boiler. It would seem necessary, therefore, that until further advances are made in furnace design and methods of operation, when a plant has reached the point of perhaps 140 per cent of its rated capacity, additional boilers ought to be added if only in the interest of a less amount of smoke. In

TABLE 5

RESULTS OF EVAPORATIVE TESTS WITH ILLINOIS COALS ON A CHAIN GRATE STOKER

Experiment Station Boiler with Tile Roof Furnace. Same Setting as Those Used for Special Smoke Tests in Tables 1 to 4.

Number	47	50	91	96	107	127	131	134
2. Duration of Trial	8.32	8.32	8.30	8.25	8.10	7.02	8.15	7.37
3. Size and Condition of Coal (*1*)	$\frac{3}{4}$–$\frac{1}{4}$(w)	$\frac{3}{4}$–$\frac{1}{4}$(w)	1$\frac{1}{2}$–0 (*2*)	(1$\frac{3}{4}$–1)	1–$\frac{3}{4}$(w)	$\frac{3}{8}$–0(w)	$\frac{7}{8}$–$\frac{3}{8}$(w)	$\frac{7}{8}$–$\frac{3}{8}$(w)
4. Per cent Moisture in Coal	10.72	11.23	11.88	7.14	9.40	21.25	19.83	19.29
5. Per cent Ash in Coal	7.31	7.64	16.89	8.42	8.21	12.58	7.68	7.19
6. Per cent Carbon in Ash Free, Dry Coal	60.41	60.41	53.95	60.41	62.43	55.94	57.39	56.35
7. Per cent Volatile Matter in Ash Free, Dry Coal	39.59	39.59	46.05	39.59	37.57	44.06	42.61	43.65
8. B. t. u. per Pound Coal as Fired	11898	11740	10036	12305	11922	9350	10274	10391
9. Thickness of Fuel Bed at Grate, inches	6	4	6	5	6	5	5	5
10. Draft Pressure in Furnace, in. of water	0.127	0.085	0.258	0.112	0.120	0.387	0.117	0.161
11. Per cent CO_2 in Flue Gases (*3*)	12.60	12.28	7.00	9.52	10.99	7.10	11.46	11.38
12. Excess Air Used, per cent	43.54	47.16	150.1	83.4	56.4	143.8	57.4	57.6
13. Temperature of Escaping Flue Gases, °F	599.0	612.0	613.4	606.0	599.0	624.0	574.0	665.0
14. Dry Coal per sq. ft. Grate Surface, per hour	22.48	22.35	26.41	22.10	20.49	27.62	20.60	27.55

TABLE 5.—(Continued)

1. Trial Number..........	47	50	91	96	107	127	131	134
15. Carbon in Ash and Refuse, per cent of Dry Coal..........	4.00	3.95	2.23	2.23	1.56	5.46	1.75	1.89
16. Steam Pressure Gage..	150.0	150.0	146.9	150.4	147.5	149.5	149.4	148.3
17. Per cent of Builders' Rated Horse-power Developed..........	109.4	109.3	103.1	101.8	99.9	99.5	101.4	133.8
18. Equivalent Evaporation from and at 212° F. per lb. Coal as Fired............	8.24	8.23	6.52	8.12	8.37	5.38	7.49	7.44
19. Equivalent Evaporation from and at 212° F. per lb. Ash Free, Dry Coal.....	10.51	10.60	9.42	9.86	10.34	8.70	10.53	10.33
20. Efficiency of Boiler..	69.93	70.75	64.60	65.32	69.00	60.18	71.76	70.61
21. Efficiency of Boiler including Grate	66.89	67.70	62.75	63.60	67.82	56.26	70.39	69.16

(*1*) Item 3—Size is given in inches. (w) refers to washed coal.
(*2*) Sixty per cent of this coal was below ¼ inch.
(*3*) The flue gases were free from carbon monoxide and smoke.

confirmation of this particular point the following discussion* is worth presenting. "The work at the government coal testing plant has been somewhat in the direction of smoke abatement, although the principal object of the work has been the determination of the value of different fuels for steaming purposes. Whenever we tested a soft coal we tried to eliminate the smoke. We have reduced the smoke 50 per cent or more, and often we burn soft coal without smoke. We have a good fireman, and he is watched all the time. Our furnace has a fire clay tile roof with a smooth lower surface, and a large combustion chamber; it is equipped with a plain grate of 40 sq. ft. We fire about fifty pounds of coal at a time on one-half of the grate area, and every two or three minutes. The furnace has three fire doors and we fire alternately in the front of the first and the third doors and in the rear of the middle door at one time, and then the rear of the first and third doors, and the front of the middle door at the next time. In this manner the distilled volatile matter is divided into three streams and this division facilitates its mixing with the hot air coming from the uncovered portions of the fuel bed.

"Another point in connection with the hand-fired furnace is that it is usually forced to burn more volatile matter than it was built for. We have often found that coal burned slowly, say at the rate of 20 pounds per square foot of grate area per hour, made no smoke at all. However, when the rate of combustion was increased to 26 pounds or more, smoke was produced, even though as great care was used in firing, and the firing was as frequent. This fact is in accordance with Mr. Bement's paper, where he states that the combustion space of a furnace is of a certain capacity, and that one should not try to burn more coal in it than the furnace was built for. The fact is that whenever a furnace is run above its capacity, it is bound to make smoke.

"I have recently noticed an interesting fact, that with a chain grate stoker in a Heine boiler furnace, no smoke was made when the rate of combustion was 42 pounds. If the same coal were burned in a hand fired Heine boiler furnace, smoke would probably be produced at the rate of combustion of 26 pounds. This seems to indicate that with the chain grate stoker more of the coal burns on the grate as fixed carbon and less of the combustible is driven off and burned as volatile matter, than is the case with a hand-fired furnace. This is probably due to the fact that with the chain grate stoker the coal is fed in grad-

*Jour. W. S. E., Dec. 1906. "Suppression of Industrial Smoke." A. Bement. Discussion by H. Kreisinger, U. S. G. S.

ually and is, therefore, heated gradually, while with the hand-firing, the coal is thrown on the top of the white-hot fire and is heated rapidly; this rapid heating is the cause of more combustible being distilled off as volatile matter and more smoke being produced.

"In conclusion I will say that the hand-fired furnace should be the last one to be considered for preventing smoke. In the first place it is rather expensive to operate, and the results are doubtful because too much dependence has to be placed on the fireman."

This discussion has been quoted because it definitely states a rate of combustion (20-26 lb.) as being about the limit for smokeless hand-firing in a certain type of furnace. It also gives good reasons why this rate may be nearly doubled on a chain grate stoker and not produce smoke. It might be well to point out, however, that while the average rate of combustion in the hand-fired furnace appears to be 20-26 lbs. for a short interval just after firing fresh coal, the rate is much higher, equal perhaps to the rate of 42 lb. of the chain grate stoker. It is entirely reasonable to suppose that furnaces will be planned that will provide for smokeless consumption of coal at much higher rates of combustion, but until they are available power plant owners should not be allowed to force boilers to such a point above capacity as will cause the furnaces to become troublesome smoke producers.

Special Mixing Devices, Piers, Wing Walls and Jets

The method of introducing the coal into the furnace will in all cases have much to do with the type of furnace which must be used to stop smoke. When the coal is fed into the furnace mechanically, as it is when stokers are used, one of the most essential elements of successful smoke prevention has been met, namely, slow and uniform gas evolution. When coal is fed by hand into a hot furnace, six shovelfuls more or less at one time, this same element has been ruthlessly neglected. The gas evolution can neither be slow nor uniform. It is also very doubtful if the proper amount of air at the right temperature will be supplied. It is to assist in correcting such known violations of correct methods of coal supply to furnaces that certain devices have been introduced which are intended to correct these initial mistakes. A steam jet is such a mixing device. When properly applied it does not let the volatile gases and air supply escape from the furnace until very intimately mixed. It has, however, two very serious objections, noise and

large steam consumption. From 5 per cent to 8 per cent of the steam made is often used in these jets. The success of the steam jet in preventing smoke, due almost entirely to its ability to properly intermingle the fuel gases and the air supply, immediately suggests the accomplishment of the same intermingling in other ways. Such ways have been devised. One of the early plans was proposed by Professor Kent in his wing wall furnace. Other plans have followed as typified by the Wooley furnace, and the Kuss mixing piers. These methods of mixing are efficient and economical and are especially to be considered in connection with hand-fired furnaces. The particular arrangement to be adopted will be determined by several factors, viz.; (a) The composition of the coal to be used. (b) Size of coal. (c) Method of firing. (d) The rate of gas evolution.

Smoke Prevention with the Horizontal Fire Tube Boiler

The horizontal fire tube boiler is still much in use in the smaller units of from 50 to 150 horse-power. It was brought into prominence in the early days of American steam boiler practice as the natural successor of the plain cylinder and flue boilers, all of which were externally fired. It soon became the standard type of boiler throughout manufacturing New England where in many places it still retains its position on account of its cheapness and its economical operation with all grades of anthracite and many grades of bituminous coals, especially those containing a high fixed carbon content.

With the coals just mentioned the combustion takes place mostly on the grate or at a short distance above it. Many plants have been installed with this type of boiler, in which the grate has been placed not more than 14 to 16 inches beneath the boiler. These plants have burned anthracite coal successfully. With the introduction of the West Virginia bituminous coals containing small amounts of volatile combustible matter the grates were lowered under this type of boiler to 24 and 30 inches with good effect. Still, with either coal, much the greater part of the heat was generated on or near the grate and the heat made available for transmission was largely radiant heat. The plates directly over the fire itself transmitted a correspondingly large part of the heat of the coal to the water in the boiler. The satisfactory performance of the fire tube boiler with eastern coals together with its availability made it naturally the boiler to be adopted by manufactur-

ers moving westward with the center of population. It is easily seen, however, that with Illinois coals carrying 30 to 40 per cent of volatile combustible matter and burned at rates which produce flame lengths of from 5 to 20 feet, this type of boiler as usually set is by no means adapted for the smokeless consumption of this kind of fuel. There is, in fact, no better method of producing dense black smoke with Illinois coal than to install a horizontal fire tube boiler with the usual furnace, and hand fire such a plant with run-of-mine coal. In such an outfit all the fundamental principles laid down elsewhere in this paper are disregarded. The method of introducing the coal directly into the hot furnace, in fine dust and large lumps, prevents slow or uniform distillation of the gases; the air supply through open doors, through holes in the fire, or through a fuel bed of varying thicknesses is neither correct in quantity nor is much of it properly heated; the mingling products of combustion come in contact with the cool surface of the plates of the boiler, reducing the temperature of the gases below the ignition temperature before combustion is completed.

Having in view these defects of the usual plan of operating the fire-tube boiler with Illinois coal, many ways suggest themselves by which these faults may be corrected. It is possible to burn Illinois coal without smoke with fire tube boilers, but the furnace requires special treatment and such settings are not common. The plans usually proposed are either low-set stokers or extended Dutch oven furnaces. When hand-firing is adopted the wing wall furnace or other form of mixing baffles or piers is of great assistance. With any of these devices careful firing is very necessary for satisfactory results. The twin brick arch furnace which keeps the gases away from the boiler plates altogether is an effective smoke preventive. Careful firing with low rates of combustion (12 to 16 lb.) per square foot of grate, assisted by automatically controlled air supply, will often enable these settings to be run so as to escape the fines of city smoke inspectors, but they can hardly be compared as to smokelessness with such settings as are illustrated in this paper. Horizontal tubular boilers are often adopted on account of their cheapness, and when such is the case the addition of any special furnace constructions or any special devices to aid in smoke prevention, is seldom given any consideration. From what has been said it is doubtless evident why this type of boiler is so frequently found to be one of our worst smoke offenders.

Burning Illinois Coal in Locomotive Boilers

The writer is compelled to admit that he does not know how to burn Illinois coal in a locomotive boiler under the usual operating conditions without making smoke. Careful firing is the most effective way of reducing the amount of smoke made, but no fireman can be found skillful enough to meet the exigencies which are always arising and to operate a locomotive boiler in service without smoke even 75 per cent of the time when using Illinois coal. It is not possible here even to enumerate the many devices which have been tried to prevent smoke production on locomotive boilers. The high rates of combustion on the grate of this boiler, often reaching 150 lb. and sometimes 200 lb. per square foot of area, produce temperatures which soon destroy all forms of fire resisting material or other constructions not backed up by water-jacketed metals. Were it not, however, for the many and sudden changes in the conditions of operation imposed by the very duties for which the locomotive is designed, all other obstacles might possibly be overcome and the locomotive become smokeless. Fortunately we can clearly see how to eliminate the smoking locomotive from the thickly populated districts by the use of the electric locomotive which now is able to meet the demands placed upon it for speed, acceleration, and tractive effort. It is also pointed out that the large power plant will now produce the electricity needed for this service with greater economy and at the same time burn Illinois coal without smoke.

How to Hand Fire Illinois Coals so as to Reduce the Production of Smoke

There are many small power plant units that are hand-fired which smoke badly. The construction of many of these furnaces is such that it is almost impossible to operate the plant without smoke. Still something might be done to reduce smoke if the fireman exercised more care in firing. Whatever can be done by the fireman in the way of properly introducing the fuel into the furnace is just so much gained. and it relieves the auxiliary mixing devices or baffles if such exist from just so much work later on. The best method of hand-firing for smokelessness is also the best method for attaining economy. There are three generally recognized methods of hand-firing: (a) The Spreading, (b) The Coking and (c) The Alternate. The first is satisfactory and generally used for anthracite; the second for coking coals and the last

for non-coking coals. It is the alternate method that is best suited to Illinois coals. This method is described as follows. The fuel bed area is divided into equal parts two, four, or six depending on the size of the entire surface. The fresh coal is fired alternately on one-half of these areas at a time at such intervals as may be necessary to hold the steam pressure. Depending on the rate of driving, these intervals will vary from one to five minutes. For small areas first one-half the surface of the fuel bed is covered and then perhaps three minutes later the other half. This method allows much of the air supply to come through the bright fuel bed and thus become heated and suitable for mixing with the highly volatile content which is being rapidly driven from the freshly fired coal on the other side. Just because fresh fuel has been spread over one part of the fuel bed, the air most needed at that moment cannot as easily flow through it, and another part of the fuel bed should be left free for its passage at that time. When the fuel bed area is very large, some checker board system of firing may be adopted which, when alternately fired and left free for air passage, will result in a large reduction in the amount of smoke produced by the too common method of spreading the coal over the entire surface at each firing. It must not be forgotten that a large supply of warm air is needed immediately after fresh fuel is spread over a part or all of the fuel bed; this is best supplied as just explained, but it may be advantageous to provide for still more air by leaving the fire doors open slightly just after each firing. There are several devices on the market which provide for an air supply over the fire, which are turned on with the opening or closing of the fire door and which can be arranged to close at the end of any desired time depending upon the rate of driving and frequency of firing found desirable. The firing of small amounts of coal at frequent intervals produces less smoke than firing large amounts at longer intervals. The latter method, however, usually proves less tiresome to the fireman and is for that reason more frequently adopted.

The Distance Between the Boiler and the Grates

Having in mind the horizontal fire tube boiler, the distance from the bottom of the boiler to the grates should be from 30 to 34 inches. At this distance the flame from Illinois coals will sweep along the bottom of the boiler and much smoke will result. Still it must be borne in mind that a large part of the heat to be obtained from the burning of the fixed carbon part of these coals is transferred to the shell in the form

of radiant heat and for this purpose the grate should be near the boiler. While it is necessary in preventing smoke, that the flames be kept from the cooling surfaces of boilers, this cannot be accomplished by simply lowering the grates under a horizontal fire tube boiler, as the writer has unfortunately been incorrectly quoted as having stated. For boilers of this type some form of furnace extending partly or entirely in front of the boilers and either hand fired or fed by stokers of the Murphy type would undoubtedly furnish a satisfactory solution to the smoke problem. As elsewhere pointed out the smoke problem is not usually satisfactorily solved with Illinois coals and the horizontal fire tube boiler. The small unit hardly warrants an automatic stoker. Desire for a cheap plant prevents any special form of furnace and so it is that this kind of a setting frequently proves to be a troublesome smoker.

The Preparation of Coal for Smokeless Burning

When the coal fed into a furnace is fairly uniform in size it is much easier to burn it without smoke than when it is of different sizes. In all the settings described in this article as smokeless, the coal burned has been of such uniformity as to meet this requirement. The standard commercial sizes are all that are required, such as No. 1, 2, 3, 4, or 5. Take, for instance, the chain grate stoker; the very principle of its operation, complete consumption of the coal while it travels the length of the furnace, makes it very evident that if small pieces of coal are just consumed, the very large pieces will not be consumed. Just to what extent it will pay to size coal for regular use is not yet very clear, but experiments reported by Mr. W. L. Abbott in a paper before the Western Society of Engineers (Sept. 1906), makes it evident that the influence of variation in size of the fuel used is of much more importance than has heretofore been generally believed. In these tests the capacity as well as the efficiency of the plant tested increased rapidly with the size of the coal used between the average sizes of 0.12 inches and 0.30 inches, after which both these factors dropped again. The following table indicates the general results obtained.

Effect of variation in size of Illinois coal screenings.

Size in inches	Horse-Power	Efficiency
.15	350	53
.20	525	60
.25	650	65
.30	725	65
.35	625	63
.40	550	60
.45	500	58
.50	525	58

Whether these results are generally applicable or whether they apply only to the conditions existing in the operation of a single plant, it is difficult to say. The plant in which these tests were made corresponds so closely to the plants described in the paper that it would seem very desirable that those operating such plants should take advantage of the results obtained and be sure that the mere matter of inattention to size should not be responsible for a capacity or efficiency loss of from five to ten per cent.

The washing of coal, which removes a considerable part of the ash and sulphur, has proved very advantageous to many plants, especially where capacity has been an important consideration. The washing itself, however, does not make coal burn without smoke. As explained elsewhere the total volume of volatile combustible distilled per hour from each square foot of grate area must determine those furnace proportions necessary, with the various methods of coal supply to the furnace, which will with any kind of coal prevent smoke. The writer desires to mention in this connection that since he began to use washed nut coal in his hot water residence heater and in his kitchen range black smoke is seldom seen coming from his chimneys. Previous to the use of this coal the kitchen range pipe required cleaning at least once, sometimes twice each year. It is now three years since this pipe was cleaned. No soot now gathers on the underside of the stove lids as was formerly the case. A fire is easily maintained eight to twelve hours in the residence heater. Experiments with two types of residence heaters, which are now available for test purposes, are in progress by the Experiment Station, and it is hoped that more exact information concerning the relative value of various coals used in this kind of furnace will soon be available. The writer confidently believes that we shall soon know how to burn Illinois coals

without smoke in residence heating boilers as readily and surely as we now know how to burn it under power plant boilers.

Briquetted coal offers some opportunity for smoke reduction in certain kinds of furnaces, and certain railroads have reported favorably on its use inside city limits. It does not appear that it can compete with raw coal, certainly not in Illinois, if any consideration is to be given to the cost. There are conditions arising where the question of cost need not be considered,—such for instance as on naval vessels in time of war. For this reason a series of tests is now being arranged between the steam engineering department of the U. S. Navy and the technologic branch of the United States Geological Survey to determine the comparative value of raw and briquetted coal on board several types of naval vessels. In these tests the question of smokeless operation will be a question of careful consideration.

Powdered fuel has been used with much success in places where the coal has not been too high in volatile combustible content, and where the cost of the coal ordinarily used exceeded five or six dollars a ton. Powdered fuel can be burned without smoke and it can be burned with excellent economy. It cannot, however, be cheaply reduced to a powder.

The writer will welcome suggestions relating to the smoke problem from engineers throughout the country, also drawings, blueprints, etc., and complete and reliable data pertaining to smokeless furnace construction.

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